Development of a competition index for young conifer plantations established on boreal mixedwood sites

by D.M. Morris[1] and G.B. MacDonald[2]

Abstract

A competition index was developed, and then used to examine the relationships between perennial competition and plantation performance. Species included were white spruce, black spruce, and jack pine for both over-wintered containers and bare root stock. A total of fifteen four-year-old plantations were used in this study representing a range of soil textures located on boreal mixedwood sites in northern Ontario.

Effective canopy cover, derived from vertical hemispherical photographs taken at the base of seedling leaders, provided an accurate estimate of the perennial woody competition affecting seedling diameter growth. Initial seedling size, defined by the stem volume at time of planting, proved to be an important covariate in the analysis.

Using the relationship between effective canopy cover and seedling root collar diameter, the following questions regarding vegetation control decision-making were addressed: 1) jack pine was more sensitive to increased levels of competition, 2) over-wintered container stock were more sensitive than their larger bare root counterparts, 3) minimal differences occurred in the pattern of growth response to competition across the range of soil textures studied, and 4) early tending treatments should be concentrated on jack pine plantations or on spruce plantations with an effective canopy cover in excess of 60.

Key Words: competition index, hemispherical photographs, boreal plantations, white spruce, black spruce, jack pine, tending guidelines.

Résumé

Un indice de compétition fut mis au point et sert à évaluer les rapports entre la compétition pérenne et le rendement de plantations. Les plantations en question contiennent des plants d'épinette blanche, d'épinette noire et de pin gris en contenants exposés à l'hivernage et des plants à racines nues. On a étudié 15 plantations de quatre ans dans cette étude. Ces plantations représentent une diversité de textures du sol et sont situées dans des peuplements de bois mixte dans le nord de l'Ontario.

Une densité de couvert effective, telle que déterminée au moyen de photographies hémi-sphériques prises au bas de la pousse apicale des semis, permet d'estimer avec précision le niveau de compétition pérenne affectant la croissance du diamètre des semis. La taille initiale des semis, telle que déterminée par le volume des tiges au moment de la plantation, s'est avérée une co-variante importante dans l'analyse.

En étudiant le rapport entre la densité du couvert effective et le diamètré du collet des semis, les conclusions suivantes s'imposent sur le plan du contrôle de la végétation: 1) le pin gris est plus sensible à l'augmentation de la compétition; 2) les plants en contenants exposés à l'hivernage sont plus sensibles que les plants à racines nues de taille plus importante; 3) la texture du sol ne compte que pour des différences minimes sur le plan de la réponse à la compétition; et 4) on doit effectuer des traitements précoces de soins sylvicoles dans les plantations de pin gris ou d'épinette dont la densité du couvert est supérieure à 60.

Mots clés: indice de compétition, photographies hémi-sphériques, plantations boréales, épinette blanche, épinette noire, pin gris, consignes de soins sylvicoles.

Introduction

The boreal mixedwood forest type represents an important element in the forest resource base of Ontario, comprising 45% to 50% of Ontario's forested land (McClain 1981). Approximately 26% of the total harvest on crown lands is obtained from these productive sites (Ketcheson 1981). If regional economic viability through a continued timber supply is to be maintained in the future, a successful reforestation program on harvested sites is essential. By definition (McClain 1981), these sites have a hardwood component that can result in severe perennial competition after harvest (Pollard 1971) which seriously jeopardizes conifer development (Oxenham 1983). Reducing competition is expensive and therefore sites should be ranked so that only high priority plantations are treated under constrained vegetation control programs. Timely release of overtopped seedlings can reduce growth losses and refill planting needs, eliminate the need for repeated tending treatments on advanced competition, and ensure that a significant conifer component exists in the new stand (Tappeiner and Wagner 1987).

The study of competition dynamics requires both a measure of the competition level occurring on a site as well as a measure of relevant crop tree responses. Since the early 1970's, a variety of competition indices have been developed to estimate the degree of interference from competitors. Some indices are based on stem diameter (Bella 1971; Hegyi 1974), canopy development (Arney 1972; Ek and Monserud 1974; Howard and Newton 1984), or proximity-based models (Daniels 1976; Wagner 1982; Weiner 1984). Most studies have considered tree response to competition in terms of absolute height or basal area. More recently, researchers have attempted to quantify crop tree size and environmental influences by using relative growth measures (Zedaker 1982; Brand 1986). The majority of research into the development of competition indices has been in pole-size or mature forest stands used to assess intraspecific competition for improving growth predictions. The limited research on competition dynamics in young plantations has been primarily in Douglas-fir plantations established on the west coast of North America (Zedaker 1982; Howard and Newton 1984; Brand 1986; Brand and Weetman 1986).

[1]Ontario Ministry of Natural Resources, Ontario Forest Research Institute, c/o Lakehead University, 955 Oliver Road, Thunder Bay, ON Canada P7B 5E1.
[2]Ontario Ministry of Natural Resources, Ontario Forest Research Institute, P.O. Box 969, Sault Ste. Marie, ON Canada P6A 5N5.

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Table 1. Species, stock type, and site conditions for plantations studied

Site #	Species	Stock type	Sample[1] size	Moisture[2] regime	Clay[3] %	Competitor density[4]			Seedling root collar diameter[5]		
						Min.	Max.	Mean	Min.	Max.	Mean
						(stems/ha)			(mm)		
1	White spruce	2 + 0	120	0	8.9	25985	167276	92529	3.6	21.3	12.0
2	White spruce	2 + 0	120	2	11.1	17408	130560	58151	4.1	29.3	14.6
3	White spruce	2 + 0	120	0	5.8	4775	111408	34099	7.7	20.7	13.5
4	Black spruce	cont.	58	5	29.6	0	100682	28082	3.5	10.6	7.1
5	Black spruce	cont.	57	2	25.5	4871	107178	30113	3.6	17.7	9.1
6	Black spruce	cont.	59	2	16.2	0	92563	24964	7.4	22.6	15.9
7	Black spruce	1½ + 1½	59	2	55.2	1624	110425	41093	5.4	20.4	12.0
8	Black spruce	1½ + 1½	60	0	8.5	0	116921	31152	5.1	24.7	12.7
9	Black spruce	1½ + 1½	58	0	11.1	1624	77947	38442	9.1	25.4	16.7
10	Jack pine	cont.	59	5	36.0	11367	131536	57188	4.1	23.2	10.7
11	Jack pine	cont.	59	0	20.9	1624	167262	42303	9.2	48.3	29.8
12	Jack pine	cont.	58	0	16.9	0	138032	50097	6.5	31.2	17.8
13	Jack pine	2 + 0	59	3	21.1	0	86067	28039	9.8	45.5	25.1
14	Jack pine	2 + 0	56	0	19.9	0	97434	28581	12.0	49.3	28.9
15	Jack pine	2 + 0	59	2	20.9	0	105554	27525	15.0	45.1	28.9

[1]Seventeen outliers (9 from black spruce samples and 10 from jack pine samples) were eliminated from analyses because of animal damage or they were found to be naturally regenerated seedlings.
[2]Moisture regime is based on a scale from 0 (dry) to 9 (very wet), as outlined by the manual for describing soils (Ontario Institute of Pedology 1985).
[3]Based on 120 samples/plantation for the white spruce areas and 60 samples for both the black spruce and jack pine areas. All samples were taken from the upper B-horizon.
[4]Based on perennial competitor counts from 40 subplots/plantation for the white spruce areas and 60 subplots/plantation for both the black spruce and jack pine areas. Area of all subplots was 6.158 m^2.
[5]Represents seedling root collar diameter four years since outplanting.

Therefore, the first objective for this study was to develop a competition index applicable to young conifer plantations established on boreal mixedwood sites in northern Ontario. The second objective was to apply the index to address the following questions: (1) how does the growth response to competition pressure differ between species and stock types, and (2) does the relationship between crop tree growth and competition vary across a range of site conditions. The answers to these questions are essential if tending is to be carried out successfully.

Methods

Data Collection

Data were collected from three white spruce (1986), six black spruce (1987), and six jack pine plantations (1988) during the fourth growing season. A total of 1080 individual seedlings were randomly sampled. These plantations were located in northern Ontario between 48°32'N and 50°14'N latitude and between 85°15'W and 92°15'W longitude, and covered a range of sites for each species and stock type. Species, stock types, and site conditions were summarized (Table 1).

A vertical hemispherical photograph was obtained in mid-July using a 7.5 mm equidistant fisheye lens, levelled with the camera focal plane located at the base of the seedling's leader. The percentage of open sky, opaque canopy, and transparent canopy were determined and used in the following formula, as outlined by Morris et al. (1990):

$$\text{Effective Canopy Cover} = [\text{Opaque \%} + (\text{Transparent \%} \times 2/3)] \quad (1)$$

The following variables were measured for all perennial competitors within a 1.4 m radius of the seedling: (1) species, (2) distance to seedling, (3) azimuth from seedling, (4) total height, (5) crown length and width, and (6) root collar diameter. It has been determined that this plot radius would include those neighbouring trees which contribute most of the competitive effect (MacDonald et al. 1990). The seedlings were destructively sampled following budset. Total height, four height increments from time of planting, crown length and width, and root collar diameter were recorded. The seedlings were then separated into current, one-year previous, and remaining plant material for foliage, branch, and stem components. A basal disc was removed for ring analysis. These components were bagged and dried at 70°C for 48 hours before dry weights were determined.

A soil sample was taken from the upper B-horizon near the base of each seedling sampled. In the laboratory, the clay fraction was determined using the Bouyoucos hydrometer method. The clay fraction was favoured as a measure of soil texture because it relates well to cation exchange capacity and moisture availability (Black 1968, Goldberg 1987). Correlations between this variable and seedling growth have been reported (MacDonald et al. 1990). Further explanation of the methodology used to collect the field and laboratory data for this study is given by MacDonald et al. (1990).

Identifying the Important Seedling Response Variables

In an earlier study to test the sensitivity of various morphological attributes of four-year-old conifer seedlings to changing levels of competition, it was found that the most consistent response variable was total seedling dry weight (Morris et al. 1990). It was also determined that root collar diameter provided the best substitute if destructive sampling was not practical. Total height and current height increment, which are commonly used for evaluation of early plantation performance, were found not to be reliable for quantifying individual seedling responses. Therefore, root collar diameter was used as a response variable to compare the different responses to changing competition levels across the range of species, stock types, and sites studied.

Table 2. Coefficients of determination (partials)[1] from multiple linear regression incorporating several competition components[2]

Site #	Total canopy	Rel. Avg. comp. ht.	Rel. Total basal area	Comp. density	Herb. %	Clay %	Stem volume[3] (at planting)	Full model
1	.169	$.031_{.20}$	.214	$.000_{1.00}$	—	$.000_{.89}$	$.003_{.69}$	.6567
2	.280	.125	.128	$.058_{.03}$	—	$.000_{.84}$	$.055_{.03}$	.5841
3	.348	.096	$.009_{.41}$	$.017_{.25}$	—	$.006_{.51}$	.108	.4175
4	.104	.094	.210	$.059_{.02}$	$.010_{.30}$	$.000_{.96}$	$.002_{.66}$	.4801
5	.202	.206	$.010_{.33}$	$.006_{.44}$	$.053_{.03}$	$.009_{.35}$	$.028_{.10}$	.5137
6	.477	.065	$.018_{.14}$	$.001_{.77}$	$.047_{.02}$	$.000_{.82}$	$.002_{.59}$	.6097
7	.207	$.029_{.05}$	.230	$.003_{.50}$	.060	$.024_{.07}$	.088	.6418
8	.317	$.040_{.02}$	.103	$.008_{.30}$	$.007_{.34}$	$.037_{.03}$	.115	.6271
9	.223	.061	.226	.057	$.028_{.06}$	$.007_{.33}$	$.007_{.36}$	.6088
10	.472	.113	.089	$.001_{.66}$	$.005_{.33}$	$.002_{.54}$	.053	.7357
11	.700	.035	.040	$.006_{.21}$	$.002_{.52}$	$.007_{.17}$	$.017_{.04}$	.8082
12	.756	$.004_{.17}$	$.007_{.08}$	.061	$.002_{.33}$	$.009_{.05}$	.057	.8975
13	.732	$.016_{.02}$	.034	$.011_{.05}$	.019	$.002_{.37}$	.048	.8622
14	.621	$.006_{.25}$	.070	$.025_{.02}$	$.001_{.72}$	$.028_{.02}$	.038	.7900
15	.666	$.001_{.72}$	$.016_{.09}$	.040	$.001_{.67}$	$.000_{1.00}$	$.003_{.47}$	.7265

[1]Coefficients of determination subscripted by significance levels which exceed $P=0.01$.
[2]Root collar diameter of crop tree was the dependent variable and the competition components were the independent variables in the regressions.
[3]Site numbers, 1,2, and 3 (white spruce plantations) were not destructively sampled therefore planted height was substituted for stem volume at time of planting.

Developing a Competition Index

MacDonald *et al.* (1990) determined that a reliable competition index should include horizontal and vertical dimensions and express the amount of competition relative to seedling size. Based on strong negative correlations with crop tree growth, the authors recommended that the following competition components be considered in the development of a competition index:

(1) effective canopy cover obtained from vertical hemispherical photographs (equation [1]),
(2) average competitor height relative to seedling height,
(3) total basal area of competitors relative to seedling basal area,
(4) competitor density, and
(5) percent herbaceous ground cover.

Procedure GLM with SAS6.03 (SAS Institute Inc. 1988) was used to evaluate these components of competition. The results from a multiple linear regression identified those competition components (independent variables) explaining significant portions of the variation in seedling root collar diameter (dependent variable). Simple correlation analysis was used to determine the amount of collinearity among the selected independent variables. A competition index utilizing the most relevant competition components which exhibited minimal collinearity was created.

At this stage, a multi-step linear regression was performed to account for important covariates. The first step adjusted individual seedling performance for the influence of initial seedling size, defined as stem volume at time of planting, by regressing root collar diameter against initial seedling size. The resulting residuals were then used as the dependent variable in a second regression with the competition index as the independent variable. When combining sites to compare growth responses of species and stock types, a second covariate was included in the regression analysis. Soil texture, in terms of percent clay in the upper B-horizon, was used to adjust root collar diameter to account for some of the differences between sites. These adjustments more clearly isolated the effects of competition on individual seedling growth after outplanting. Samples demonstrating little variation from the mean have resulting regression equations with slopes approaching zero, indicating a low degree of sensitivity to changing competition levels. A high level of sensitivity is associated with those populations with large variations from the mean. A series of graphs illustrated the relationship between root collar diameter and woody perennial competition levels for the various species, stock types, and sites.

Results and Discussion

Development of Competition Index

In relative terms, effective canopy cover (from equation [1]) was the most relevant competition component in the multiple linear regression (Table 2) and was significant at $P = 0.01$ for all 15 sites. Average competitor height relative to individual seedling height and total competitor basal area relative to individual seedling basal area also proved to be important competition components, but their significance was not consistent across all sites (Table 2). Using simple correlation analysis, it was determined that collinearity existed between average competitor height, total competitor basal area, and effective canopy cover. These three measures of competition quantify competition in a similar manner and therefore only one should be used, namely effective canopy cover, in estimating the amount of perennial competition on a given site.

Additional variables were included in the multiple linear regression model which did not estimate the amount of perennial competition, but may have influenced crop tree performance. These included percent herbaceous cover, percent clay in the upper B-horizon, and initial seedling size. Of these, only stem volume at time of planting or planted height in the case of the three white spruce plantations, consistently accounted for a significant portion of the variation in root collar diameter for the 15 plantations studied (Table 2). A weak relationship between this variable and effective canopy cover existed. Any significant negative correlations between effective canopy cover and stem volume at time of planting represent spurious correlations as operational tree planters cannot be expected to link stock size to anticipated competition levels nor would they consciously attempt to plant small stock under heavy competition, which is indicated by negative correlation coefficients.

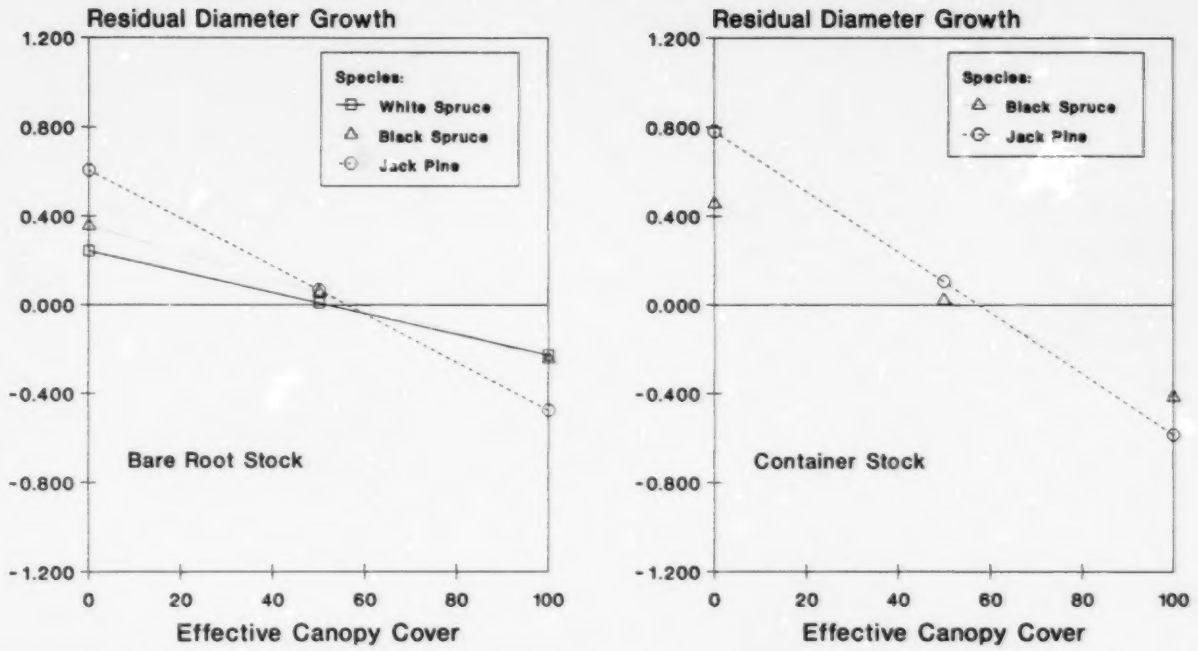

Figure 1. Regression lines comparing the sensitivity of root collar diameter to competition for the species and stock types studied four growing seasons after outplanting.

The results suggest that only one competition measure (effective canopy cover) and one covariate (stem volume at time of planting) be used when evaluating plantation performance. The interaction of these two variables was not significant at $P=0.10$ in fourteen of the fifteen sites studied and, therefore, need not be included in the model.

Species and Stock Type Comparisons

The regression lines of seedling root collar diameter, adjusted for initial size, regressed against effective canopy cover are presented (Fig. 1). In this figure, the *Y*-axis represents the residuals from the regression of root collar diameter (dependent) on stem volume at time of planting (independent). The resulting regression of these residuals (dependent) on effective canopy cover (independent) demonstrates jack pine's poorer performance under high competition levels, and high growth potential at low levels. The spruces, on the other hand, illustrate a lower degree of sensitivity to competition resulting in minimal increased growth potential over the mean growth (mean = 0.000 in Fig. 1) even at extremely low levels of competition. The difference between white and black spruce (bare root stock) is negligible as the 95% confidence intervals for B_0 and B_1 include the means of the regression lines for the alternate species (Table 3). White and black spruce are shade tolerant species and rated on a scale of 0 to 10 they are 6.8 and 6.4, respectively (Fowells 1965). Jack pine is significantly more shade intolerant, rated at 1.8 on Fowell's scale. The slopes of the regression lines for jack pine (Fig. 1) are significantly different from those of the spruces for plantations established with either over-wintered container or bare root stock. The 95% confidence intervals for B_0 and B_1 for the spruces do not include the means for jack pine (Table 3). The degree of sensitivity of the jack pine and black spruce containers appears to be greater than that of their bare root counterparts, although the mean for B_1 in the regression line for black spruce (bare root stock) is included in the 95% confidence intervals for the black spruce (container stock) regression line.

Site Related Variations in Growth Responses

It would seem reasonable to expect that the growth responses of the three species may vary greatly across a range of site conditions. Although they are all boreal species, their

Table 3. Regression results of root collar diameter (dependent), adjusted for initial seedling size and site differences, regressed on competition index (independent) for the species and stock types studied

Species	Stock type	*n*	Coefficient of determination	*Y*-intercept (B_0)	95% Confidence interval	Slope (B_1)	95% Confidence interval
Sw	2 + 0	360	.1898	.2435	$.1706 \leq B_0 \leq .3164$	−.0047	$-.0061 \leq B_1 \leq -.0003$
Sb	cont.	174	.3697	.4554	$.2727 \leq B_0 \leq .6381$	−.0087	$-.0120 \leq B_1 \leq -.0054$
Sb	1½ + 1½	177	.3283	.3564	$.2114 \leq B_0 \leq .5014$	−.0060	$-.0084 \leq B_1 \leq -.0036$
Pj	cont.	174	.7802	.7956	$.6488 \leq B_0 \leq .9424$	−.0138	$-.0162 \leq B_1 \leq -.0114$
Pj	2 + 0	174	.7179	.6056	$.5345 \leq B_0 \leq .6767$	−.0108	$-.0120 \leq B_1 \leq -.0096$

Table 4. Regression results of root collar diameter (dependent), adjusted for initial seedling size, regressed on competition index (independent) demonstrating site differences for species and stock types studied

Site #	Species	Stock type	n	Coefficient of determination	Y-intercept (B_0)	95% Confidence interval	Slope (B_1)	95% Confidence interval
1	Sw	2 + 0	120	.2071	.2474	$.1035 \leq B_0 \leq .3913$	−.0063	$-.0089 \leq B_1 \leq -.0037$
2	Sw	2 + 0	120	.3730	.5494	$.3914 \leq B_0 \leq .7074$	−.0073	$-.0097 \leq B_1 \leq -.0049$
3	Sw	2 + 0	120	.3921	.3070	$.2120 \leq B_0 \leq .4020$	−.0077	$-.0099 \leq B_1 \leq -.0055$
4	Sb	cont.	58	.1326	.0425	$-.2373 \leq B_0 \leq .3223$	−.0044	$-.0092 \leq B_1 \leq -.0004$
5	Sb	cont.	57	.2435	.3187	$.0439 \leq B_0 \leq .5935$	−.0086	$-.0104 \leq B_1 \leq -.0032$
6	Sb	cont.	58	.4933	.9765	$.7421 \leq B_0 \leq 1.211$	−.0127	$-.0169 \leq B_1 \leq -.0085$
7	Sb	1½ + 1½	58	.4178	.3128	$.1508 \leq B_0 \leq .4748$	−.0067	$-.0097 \leq B_1 \leq -.0037$
8	Sb	1½ + 1½	60	.5277	.5142	$.2614 \leq B_0 \leq .7670$	−.0108	$-.0150 \leq B_1 \leq -.0066$
9	Sb	1½ + 1½	58	.2889	.6527	$.4047 \leq B_0 \leq .9007$	−.0074	$-.0112 \leq B_1 \leq -.0036$
10	Pj	cont.	58	.5634	.5638	$.1116 \leq B_0 \leq 1.016$	−.0105	$-.0163 \leq B_1 \leq -.0047$
11	Pj	cont.	59	.7237	1.2786	$1.449 \leq B_0 \leq 1.109$	−.0169	$-.0201 \leq B_1 \leq -.0137$
12	Pj	cont.	57	.8207	.4258	$.2988 \leq B_0 \leq .5528$	−.0139	$-.0165 \leq B_1 \leq -.0113$
13	Pj	2 + 0	59	.7947	.6041	$.4835 \leq B_0 \leq .7247$	−.0115	$-.0133 \leq B_1 \leq -.0097$
14	Pj	2 + 0	56	.7214	.6529	$.6507 \leq B_0 \leq .6551$	−.0103	$-.0125 \leq B_1 \leq -.0081$
15	Pj	2 + 0	59	.6666	.6308	$.5126 \leq B_0 \leq .7490$	−.0121	$-.0145 \leq B_1 \leq -.0097$

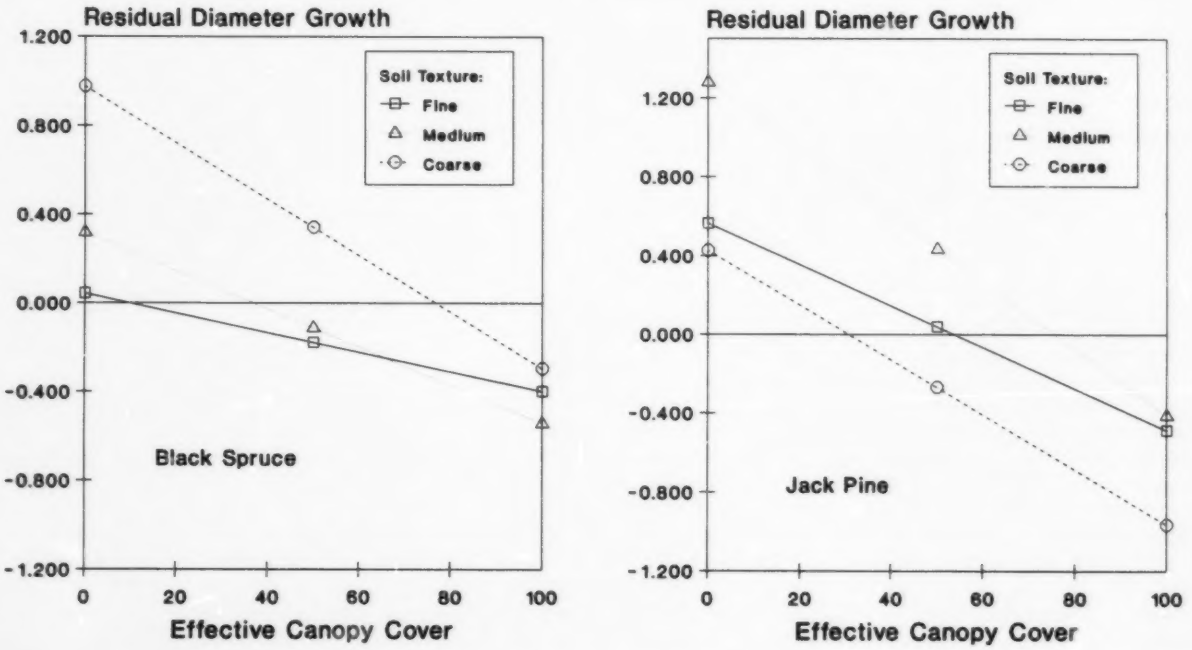

Figure 2. Regression lines comparing the sensitivity of root collar diameter (over-wintered container stock) to competition outplanted on sites with a range of soil textures.

silvics are substantially different. These unique characteristics may predispose a species to slow growth when placed on an "off-site" situation by altering its competitive tolerance. Competitive tolerance is defined by Goldberg and Fleetwood (1987) as the ability of an organism to continue to perform relatively well in the presence of competitors. The different patterns of growth response for the species and stock types outplanted on different site conditions are illustrated in Figures 2 (container) and 3 (bare root). Sites studied ranged from fine-textured, moist conditions to coarser-textured, drier conditions (Table 1), although a wide range was not possible for all species and stock types.

The results demonstrate that the slopes of the regression lines for white spruce are similar (Table 4), indicating that the competitive tolerance of white spruce is not affected by soil texture (Figure 3). White spruce is more exacting in its nutrient and moisture requirements than associated spruces or pines (Paine 1960, Swan 1960). These requirements are, in part, related to its shallow rooting habit (Hosie 1979). Percent clay ranged from 11.1% (fine) to 5.8% (coarse) for the white spruce sites studied. This range is low when compared to those of the black spruce and jack pine sites (Table 1). The "finest-textured" site (clay fraction – 11.1%, moisture regime – 2) has the highest potential for growth when competition is excluded. The mean B_0 for the corresponding regression line is 0.5494 and is not included in the 95% confidence intervals of B_0 in the regression lines for the other two sites (Table 4). This suggests that moisture availability may be an important factor in early seedling growth for white spruce regardless of competition level. Testing this hypothesis would have been aided if one of the selected sites had a substantially higher clay fraction (eg. greater than 30%).

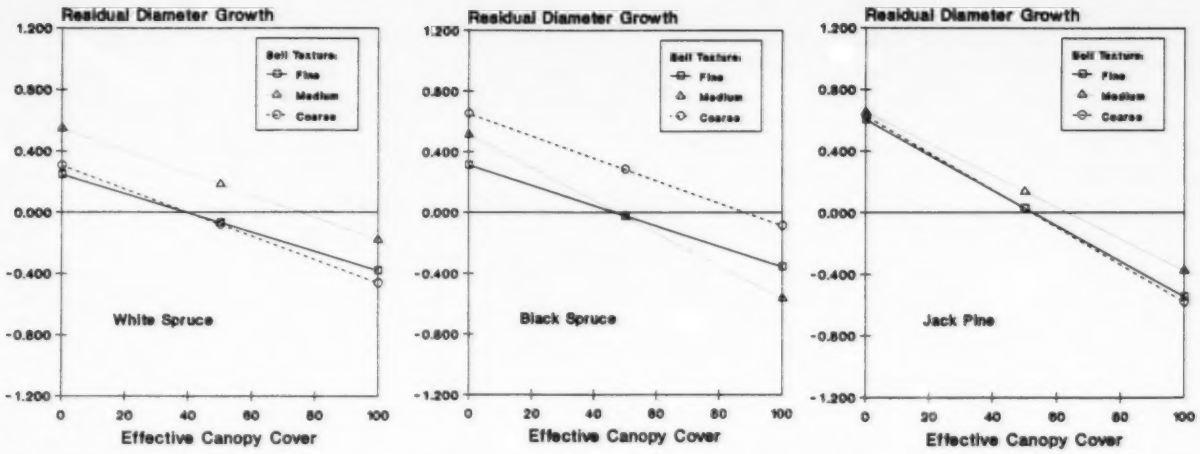

Figure 3. Regression lines comparing the sensitivity of root collar diameter (bare root stock) to competition outplanted on sites with a range of soil textures.

Table 5. Projected root collar diameters converted from linear regressions using equation [2] for each species and stock type studied

Species	Stock type	Projected root collar diameter			Decrease from max. potential dia. at cover = 50	Canopy cover to reduce root collar dia. by 30%	Actual mean[1] canopy cover
		Cover = 0	Cover = 50	Cover = 100			
		(mm)			(%)		
Sw	2 + 0	16.59	13.45	10.32	18.9	79.4	52.2
Sb	cont.	15.62	10.95	6.28	29.9	50.2	52.6*
Sb	1½ + 1½	18.74	14.60	10.45	22.1	67.9	59.0
Pj	cont.	35.01	21.56	8.10	38.4	39.1	57.7*
Pj	2 + 0	44.31	29.41	14.51	33.6	44.6	55.9*

[1]An asterisk denotes the tending is required.

Black spruce is also characterized by shallow root development, penetrating only to a depth of 3-4 cm in two years (Place 1955). A tap root does not develop, although sinker roots can be found on older trees. This rooting characteristic may be responsible for the reduced competitive tolerance on the coarse sites illustrated in Fig. 2 (container) and Fig. 3 (bare root). Mean slopes for the regression lines decreased from −0.0044 (fine) to −0.0127 (coarse) for the containerized stock and, although less pronounced, from −0.0067 to −0.0108 for the bare root stock (Table 5). The 95% confidence intervals did include the mean B_1 in the regression line for the bare root stock. Although measurement of effective canopy cover is designed to quantify incoming light, it indirectly relates to moisture and nutrient requirements of the competitors. Therefore, these factors may also become limiting at high competition levels on coarse sites.

Jack pine is one of the most shade-intolerant species and this intolerance leads to significant reductions in early seedling growth as indicated previously (Fig. 1). The formation of a tap root in jack pine allows this species to occupy a wide variety of site conditions. By the second growing season, jack pine seedlings typically have tap roots 26 to 30 cm in depth and a lateral spread of feeder roots up to 60 cm (Stoeckeler and Limstrom 1942). Therefore, jack pine is capable of maintaining itself on very dry sandy or gravelly soils where other species fail to become established. With this ability to access limited moisture supplies, the competitive tolerance of jack pine is unchanged across the range of sites (Figures 2 and 3), although the maximum growth potential (y-intercept) is greatest on site # 11 and # 14 (Table 4). These sites represent the medium-textured sites with clay percentages of 20.9 and 19.9, respectively. Pawluk and Arneman (1961) also found that jack pine growth improves with an increase in the percentage of fine particles in the upper soil layer until 30%, where it declines sharply.

Silvicultural Considerations

Based on its sensitivity to changing levels of competition (Figures 1 - 3), jack pine (container or bare root stock) is a poor candidate species for plantation establishment on any site with competition problems. In these figures, however, 0.000 residual diameter represents the mean root collar diameter for each regression line. This mean diameter varies greatly from as low as 7.1 mm for black spruce to 29.8 mm for jack pine (Table 1). Therefore, to get a clearer picture of the anticipated absolute root collar diameter for the various species and stock types, residual diameters should be converted back into absolute values, as follows:

$$\text{Root Collar Diameter} = (1 + \text{Residual Diameter}) \times \text{Mean Diameter} \quad (2)$$

For all species and stock types studied, the following calculations were made from the derived regression lines and summarized in Table 5: (1) projected root collar diameters at three levels of effective canopy cover (0, 50, and 100), (2) the percentage of diameter loss when effective canopy cover increases from 0 to 50, (3) the level of effective canopy cover required to reduce root collar diameter by 30% of the maximum (effective canopy cover = 0), and (4) the actual

mean total canopy cover for the plantations included in this study. The results of these calculations demonstrate that although over 30% of the potential diameter growth is lost at a competition index of 50 for jack pine, these diameters are still significantly greater than the maximum growth potential for the spruces (effective canopy cover = 0). Tending is expensive and becomes increasingly more expensive as the level of competition control is increased. Therefore, it may prove to be cost effective to accept greater reductions in potential growth on jack pine plantations and maintain higher levels of competition on site, rather than performing costly tending to maintain competition levels near zero on spruce plantations for only marginal increases in diameter growth. Additionally, the potential root collar diameter is substantially greater for jack pine as it is capable of a 60% (bare root) to an 80% (container) increase over the mean seedling diameter if competition is completely eliminated versus approximately a 35% increase for the spruces (Table 3).

From an economic standpoint, the percentage of area planted to a given species in a management unit is largely a function of the future demand of local markets. From a silvicultural standpoint, however, what is the advantage of planting spruce if jack pine outperforms both white and black spruce even under competition stress? The answer to this question, in part, may be related to the risk of mortality of individuals from each species. Although individual jack pine seedlings are significantly larger than their spruce counterparts (four years after outplanting), the total number surviving individuals per unit area may be substantially lower. This study used a "censured sample" by sampling only the seedlings present four years after planting. The next logical step is to establish a trial which traces the survivorship and growth of individuals from the time of planting for various species/stock type combinations. Combining the resulting mortality and growth rates, one would be able to provide a better estimate of productivity per unit area.

Spruce's ability to withstand high levels of competition for long periods has been documented. Spruce have been found to survive 40 to 50 years of suppression and still respond to release (Cayford 1957). For the purposes of the following tending scenario, a tending threshold of 30% growth reduction from the maximum potential of the species planted was selected. It should be noted that this 30% threshold is not universal, but must be based on a host of interrelated factors (e.g., management objectives, treatment options, treatment costs, treatment effects, economics of enhanced stand growth). However, when using this percentage, the results from this study indicate that effective canopy cover must reach 79.4 for white spruce, 50.2 for black spruce (container), 67.9 for black spruce (bare root), 39.1 for jack pine (container), and 44.6 for jack pine (bare root) before release treatments would be necessary (Table 5). Comparing these threshold effective canopy cover values to the actual mean values (Table 5), all the jack pine plantations (container and bare root) clearly require tending. Tending of the four-year-old spruce plantations generally would not be necessary, although the threshold value of 50.2 for the black spruce (container) was slightly under the actual mean value of 52.6 (Table 5). Based on these results, a decision to treat all plantations would not be practical nor would it be necessary with only a minimal loss in growth potential.

The practical application of using vertical hemispherical photographs to quantify competition levels must be considered. If it is necessary to accurately quantify the amount of perennial competition affecting crop tree growth, the use of effective canopy cover derived from hemispherical photographs should be considered. After the initial equipment costs, field and laboratory operations can be considerably less than obtaining detailed mensurational data. For this study, each photograph (including locating randomly selected coordinates, setting up and levelling tripod, removing crop tree from view of camera, and taking the photograph) took an individual five minutes. The laboratory time required to determine the opaque and transparent fractions on each photograph, required to calculate effective canopy cover (Equation [1]), can be substantially reduced using automated measurement systems based on the opacity of the corresponding negatives (Chan *et al.* 1986). Obtaining sufficient mensurational data on the developing canopy to approximate the data obtained from the fisheye photograph took a crew of two people 1.3 hours. For the 1080 samples used in this study, the field work required to take the photographs was 90 hours or 11.25 man days. The collection of mensurational data on the surrounding competitors took 351 man days. The data entry, verification, editing, and analysis could easily take an individual an additional 2 months to complete. These labour intensive procedures associated with the mensurational measurements are clearly not practical. Therefore, if accurate assessments of competition are required, then the use of hemispherical photography is a viable option.

An additional question must be addressed: Is it necessary to accurately evaluate competition on an operational basis? If one wants to feel confident in their assessment and subsequent decision to postpone tending, a quantitative assessment is essential. If this is not desirable, one can still use the species/stock type comparisons, identified in Figures 1 – 3, to properly match species with anticipated competition problems and to rank plantations based on species trends for urgency of tending. It seems most appropriate that the need for accurate quantitative assessments of competition would be on other research projects examining young plantation establishment, growth, and development. For example, experiments designed to evaluate the effects of stock and planting quality, scarification, fertilization and herbicide treatments, or thinning on the development of individual seedlings may find it useful to analyze the interaction between competitive level and the treatment being studied.

Conclusions

Several key questions regarding the relationship between woody perennial competition and plantation performance four years after outplanting have been addressed in this study. The answers to these questions are as follows:

(1) Significant differences in the sensitivity to competition did occur between species, but minimal differences occurred between stock types. Jack pine, classed as a shade intolerant species, was substantially more sensitive to increases in competition than were the more tolerant spruces. Over-wintered container stock tended to be more sensitive then their larger, bare root counterparts.

(2) Minimal differences occurred in the pattern (slope) of growth response to competition across the range of soil

textures studied, although greater maximum growth potential without competition occurred on the medium- to fine-textured soils for all species and stock types.

(3) Jack pine, one of the fastest growing conifers during early development, outperformed both white and black spruce in absolute diameter growth even under competitive stress, although significant reductions from the maximum growth potential had occurred.

(4) Early tending treatments should be concentrated on jack pine plantations or on spruce plantations with an effective canopy cover in excess of 70, if 30% growth reduction from the maximum is used as a tending threshold.

(5) If accurate assessments of competition are required, the use of effective canopy cover, obtained from vertical hemispherical photographs, can be cost effective as field assessment and laboratory work can be significantly reduced. Accurate assessments of competition lend themselves more readily to other related research projects rather than to operational evaluations of plantation performance.

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